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Optimization as an innovative design approach to improve the performances and the functionalities of mechatronic devices

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Abstract

The economic context, more frequent needs and increasingly more requirements expressed by customers imply to design more complex products but using less time-consuming approaches. New products are currently integrating technologies from different fields. Mechatronic devices are some examples and are increasingly more present in our daily lives: vehicles, trains, and airplanes… To improve and design such devices, new multidisciplinary design approaches and technologies are required. Research works presented in the paper fit within this context and aim to improve the performances and/or the functionalities of mechatronic devices by integrating optimization tools within the preliminary design stage. The approach presented in this paper should be seen as a guideline to better design and optimize mechatronic devices by supporting the designer during the development stage. As shown in the presented approach, the optimization can now be used as an automated tool to develop a solution layout that follows design concepts created using tools such as TRIZ and evaluate them through the embodiment process. The methodology is the heart of our paper and has then been applied the innovative design of an X-Y table to produce products by laser cutting. Results are finally presented and discussed, and outlooks are introduced.

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Keywords: *optimization; mechatronic systems; embodiment design; preliminary design*

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1. Introduction

Constant evolving needs and markets implies that new products are always more efficient, less expensive, and the design time always lower. This also implies to combine technologies from several disciplines, such as mechatronic products that synergistically integrate solutions from mechanics, electronics, control and computer engineering [1], that are the heart of our work. Mechatronic system [2] design is therefore very difficult because such devices tend to be even more complex and because most current modeling tools operate over only a single domain [3]. This then requires new approaches to design and optimize mechatronic devices.

This paper deals with the use of optimization as a method to improve mechatronic designs from the embodiment stage. To design a mechatronic system, it is required to develop four different subsystems [4]:

- A “base structure”, which often consist of a mechanical structure or a material,
- One or more actuators that can act on a machine or a process to change its behavior or states,
- One or more sensors to provide information on the current state of the machine that can be analyzed and processed by an information processing device,
- One or more information processing device, often a computer or an embedded system, analyze and process the information given by the sensors and control the actuator to obtain the desired behavior. The control law synthesis consists of the main part of these processing devices.

The optimization process of mechatronic devices often occurs during the detailed design process [5] and is restricted to a sizing problem solving: optimization methods are used to identify the best parameters that solve the problem without affecting the architecture of the system. Such optimization is therefore used to improve performances of an already designed device and is then constrained by choices made during early design steps [6]. The design phase of a product is responsible for only 5% of the cost of the product but can determine 75% of the manufacturing costs and 80% of the product quality [7-9]. So, the optimization of an already designed product has a limited efficiency. That is why, it is important to improve the effectiveness of the optimization by doing it earlier in the design phase [10].

Following [11] optimization is mostly used as a redesign process to enhance the performance of a system during the detailed design phase of the product, once it has been developed during the conceptual and embodiment phases [12] using other advanced tools, such as TRIZ [13, 14], Case- Based Reasoning [15], etc. This development is often done using design models that had been created for monodisciplinary system design [6], such as the systematic approach proposed by Pahl and Beitz [5]. In 1994, Cooper [16] proposed a “third generation new product process”, the stage-gate process, which has widely been adopted by R&D departments and gain legitimacy each year. It is moreover based on the three development, evaluation and selection steps that are fairly closed from those used in optimization. In 2004, the mechatronic community, as a guideline to develop multidisciplinary devices, adopted a design model for mechatronic system, known as the V-cycle [4].

The work presented in this paper deals with the innovative design process [17] of mechatronic systems. Starting from a principle solution or concept of a technical concept, our research work aim to propose a design approach to develop and optimize the mechatronic design layout. To perform this, our contribution should solve the following problems:

- The multidisciplinary aspect of the mechatronic device and the integration of different technologies from mechanical, electronic, control and computer engineering should been considered;
- The architecture, the structure of the system should also been modified during the process;
- The parameters of a candidate structure should be optimized along criteria that can also be used to evaluate the solution among the design problem;
- The best mechatronic solution(s) that solves the given design problem according to the previously defined concept of solution should be selected.

In previous contributions [18-21], we presented the embodiment design approach that uses parametric, topology or combinatorial optimization techniques to design a mechatronic device and improve its functionalities or performances. In the present paper, we now present how this approach can be applied on a study case, the improvement of a laser cutter.

The paper is subdivided into four parts. The state of the art concerning our problem is firstly introduced. Then the approach we developed to design and optimize the mechatronic layout that shapes the design problem and concepts is then briefly presented. This approach is then applied to a case study that aims to design and optimize an XY table for laser cutting. And, further developments regarding the automated design and the characterization of the proposed approach are finally introduced.

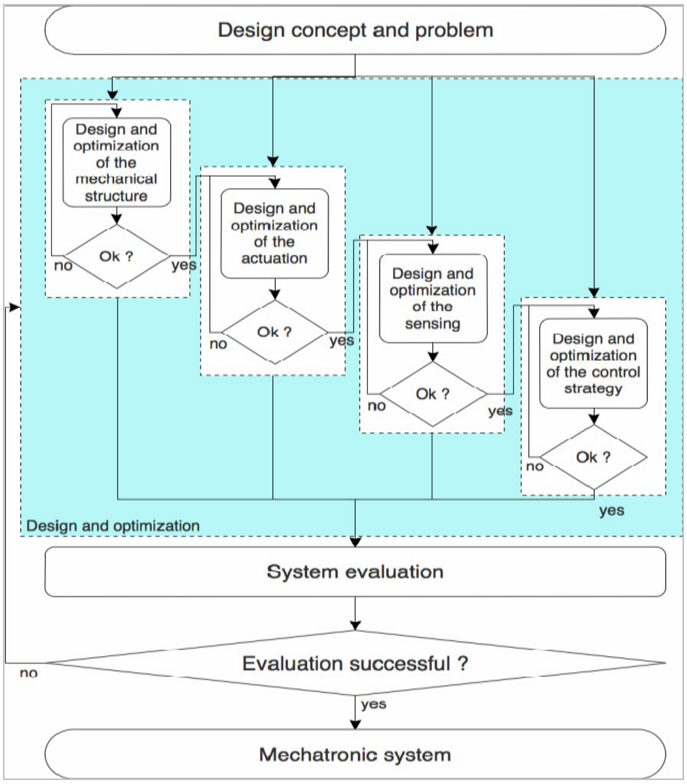

Figure 1. Optimization-based embodiment design approach for mechatronic systems.

2. Optimization-based embodiment design approach

In previous contributions [18-21], we presented the optimization-based design approach presented in Figure 1 to build mechatronic layouts from a set of design concepts developed from TRIZ [22-24] or other inventive design approaches. To develop this approach that can be used to integrate optimization during the embodiment development stage of mechatronic systems, the following problems had to be solved:

- In which order should the different subsystems of a mechatronic system be designed?
- How to use optimization as a method for the embodiment
- design?
- How optimization can act on the topology of a mechatronic device?

2.1. Subsystems design

These requirements imply to design these subsystems using a hierarchical design approach that is presented in Figure 2.

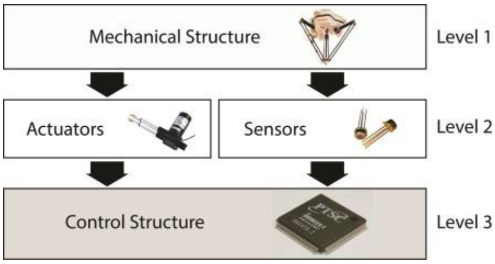

Figure 2. Hierarchical design approach.

The design approach considers the three following design levels:

1. In the first level, the skeleton of the mechatronic system consisting of the mechanical structure is designed.
2. Based on the choices made for the mechanical structure, actuation and sensing subsystems are defined. This selection should be made from the skeleton, as it will constrain the amount of possible solutions: for example, the type of motion an actuator should apply depends on the type of joint from the kinematic structure.
3. Finally, once the mechanical structure, the actuators and sensors have been selected, we get all required information to synthetize the control strategy. The control structure will indeed strongly depend on the nature of the mechatronic system to be designed.

In the different stages and levels, optimization is integrated in the embodiment design phase to optimize both the structure and the parameters from the subsystem. These subsystems are designed using an evolutionary-based approach that includes the following steps:

1. Definition of the solution candidates that can be used to embody one specific design concept. This step should normally lead to the completion of a morphological matrix. This step could be realized by experts or be done using Case-Based Reasoning [15, 18, 25] tool to reuse and adapt existing solutions from a case or solution base. Data-mining tools may also be considered to extract data from patents or other sources (Internet for example) and index them in the case database and therefore improve the number of cases from the database with cases that does not come from the company itself. This could help improving the expectable invention level [22].
4. Based on the morphological matrix and after verifying if there are some solutions that are not compatible with some others from the matrix, computational evolutionary algorithms, such as NSGA-II [26], are used to build a mechatronic design layout by combining solutions from the morphological matrix.
5. Another optimization loop is then applied to identify the best parameters of each mechatronic subsystems.

The hierarchical based approach enables the previously designed subsystems to be integrated within the design process of the further subsystems.

The authors kindly invite the reader to consider [18, 19] for more precise information regarding the development and the details of the approach.

3. Design and optimization of an XY table for laser cutting applications

In the following section, we present how we applied the approach introduced above to the improvement of an XY table for laser cutting purposes.

3.1. Design problem

In order to build our design problem, we considered a laser cutter. Usual uses of the laser cutter may be decomposed in three steps:

1. A sheet of material should be manually positioned on the support; this operation requires approximately 4 to 7 minutes, depending on the abilities of the user.
2. Then the laser performs the cutting operation, and required less than 2 minutes to cut 500 pieces.
3. Finally, the user should manually remove cut parts from the laser cutter. This operation again requires several minutes to perform it (4-7 minutes for 500 pieces).

Based on information provided above, we may observe that the use of such a system within a production line would not be efficient because of the low productivity of ca. 2500 pieces per hour.

The objective of the design problem of this case study will be to improve the productivity of the laser cutter, in order to satisfy those requirements. This problem implies two major subproblems:

1. Optimization of the loading-unloading process of the material sheet;
2. Optimization of the cutting process (improvement of the cutting path, the characteristics of the laser).

However, in order to make the optimization process simpler, we decided to focus on the optimization of the loading-unloading process of the sheet of material, as it is the more time-consuming subproblem.

3.2. Definition of the design concepts

Based on the optimization problem defined in subsection 3.1, we could define some design problems we want to solve using the proposed approach:

- Move the sheet of metal
- Actuate the sheet of metal
- Adjust the velocity and the torque

Guide the movement

Table 1. Morphological matrix for the loading-unloading problem of the laser cutter

Problem	Solution 1	Solution 2	Solution 3
Move the sheet of metal	Conveyor belt with pulleys		
Actuate the sheet of metal	DC motor	Permanent magnet synchronous machine	
Adjust the velocity and the torque	No reductor	Simple gearbox	Planetary gearbox
Guide the movement	Guiding rails		
Control the move	PI speed	PID speed controller	

In order to solve these problems, we considered the candidate solutions presented in the morphological matrix (Table 1). Once the solution candidates have been selected, we modeled each solution separately using Matlab/Simulink with the SimPowerSystems and SimDriveline toolboxes.

Figures 3 to 6 present some models used for our candidate solutions.

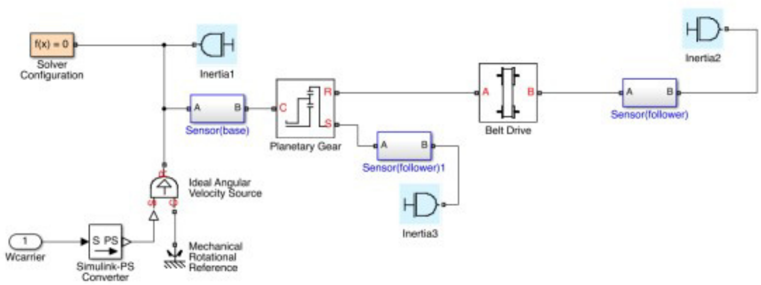

Figure 3. Simulink model of the mechanical structure (belt drive) with planetary gear reductor.

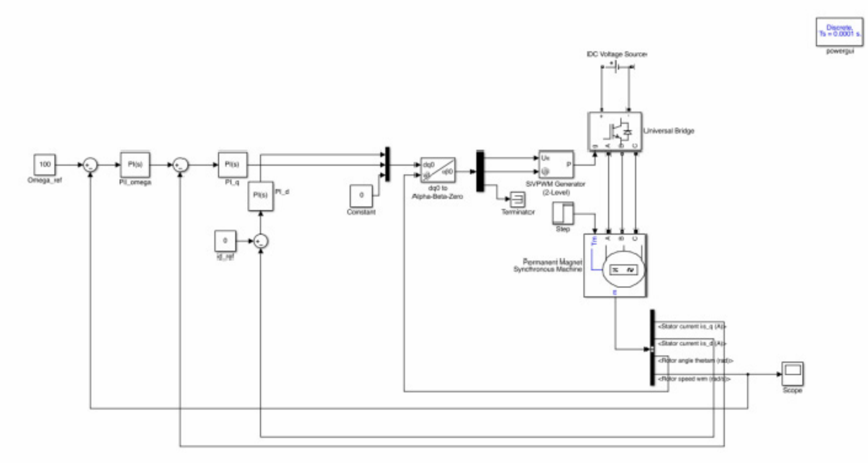

Figure 4. Simulink model of PWM-driven PMSM with PI current controllers.

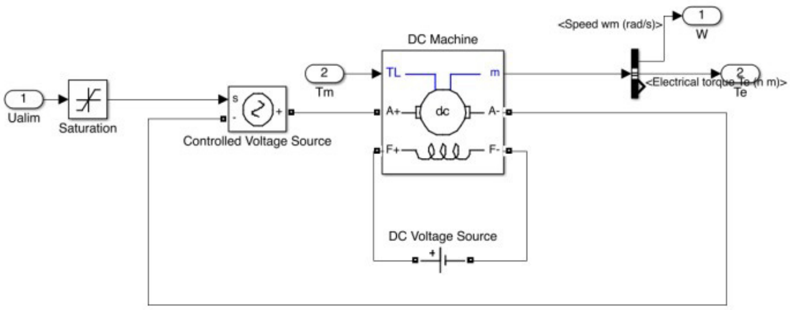

Figure 5. Simulink model of the DC motor.

3.3. Optimization problem

Once the Simulink model is ready, we can now start setting the optimization script that will be used to set parameters from the model, simulate the Simulink model and evaluate the optimization objectives and constraints.

We defined our problem as follow:

- Objective 1: maximize the velocity of the mechatronic device
- Objective 2: minimize the electrical power required for the motion
- Objective 3: minimize the integrated square error between reference velocity and the real velocity (output of the model).
- Constraint: the torque applied to the pulley of the conveyor belt should be more than 15 Nm.

We considered this torque constraint in order to ensure the torque applied by the motor with the power transmission gearbox is more than the resistive torques resulting from the frictions, weight of the materials, … .

During the optimization process, which has been performed using ModeFrontier software tool, the following parameters were optimized:

- Subsystems selectors: position of the different switches from the Simulink model
- Parameters of the mechanical structure: tooth ratio of the gearboxes and radius of the pulleys
- Parameters of the actuators: in order to make the optimization results more realistic, the motor is selected among motor presets that are proposed in the PMSM or DC motor blocks.
- Parameters of the controllers: current controllers (for the PMSM) and velocity controllers (PI or PID controllers).

A Matlab script was created to select technical solutions. For each solution, an identifier is provided, which correspond to its index in the morphological matrix. Then, solutions were combined using combinatorial optimization tools to identify the optimal solution.

3.4. Results and analysis

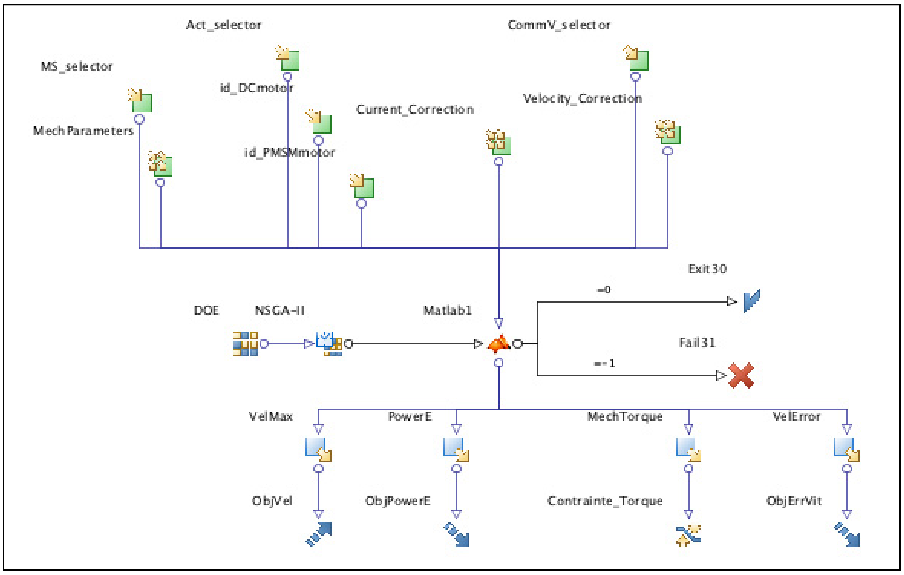

Figure 6. Screenshot of the optimization problem on ModeFrontier.

Using ModeFrontier (see Figure 7) configured as follows:

- Optimization algorithm: NSGA-II
    - Number of generations: 100
    - Crossover probability: 0.9
    - Mutation probability: 1
- Design of Experiments (DOE):
    - Method used: Sobol
    - Number of designs: 20

That optimization led to the results presented as follows in approximately 36 hours using MacBook Air Core i7 computer, 5 concurrent design evaluations (one simulation took approximately 1 min 30 each).

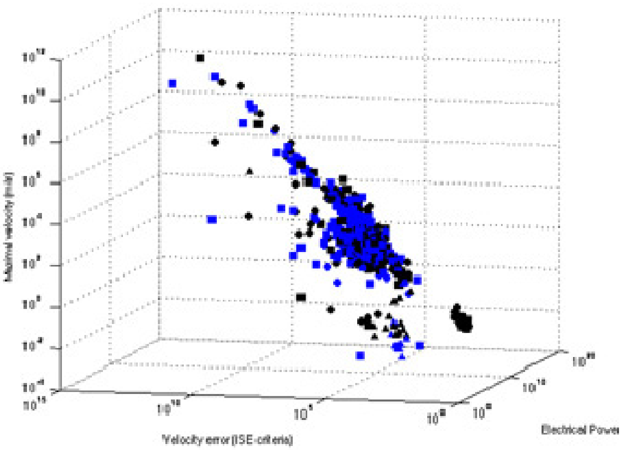

Figure 7. 3D representation of the optimization results

The legend used in these representations is the following:

- Marker type: mechanical structure
    - Square: belt without gearbox
    - Triangle: belt with simple gears
    - Round: belt with planetary gearbox
- Marker Size: type of actuator
- Color: velocity control strategy
    - Black: PI velocity controller
    - Colored: PID velocity controller

Based on the following results, we can see that the best structure is:

- Conveyor belt with simple gearbox
- ca. 10kW DC motor
- PI velocity controller

However, we may see that a compromise should be done between electrical power and the velocity of the system. In order to further increase the performances, non-mechanical interactions may then be considered, in concordance with the TRIZ principle number 28, by changing the actuators with magnetic or pneumatic systems.

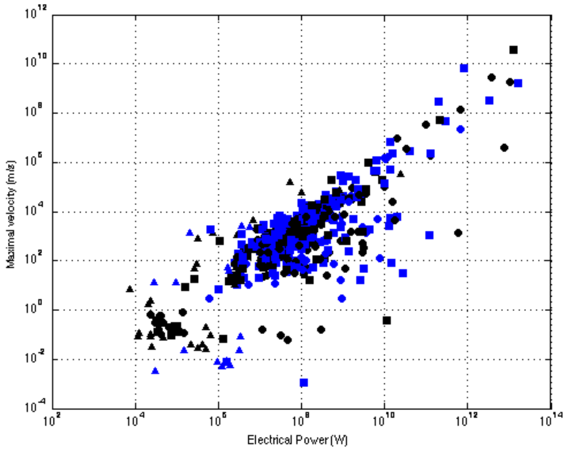

Figure 8. Comparison between maximal velocity and electrical power.

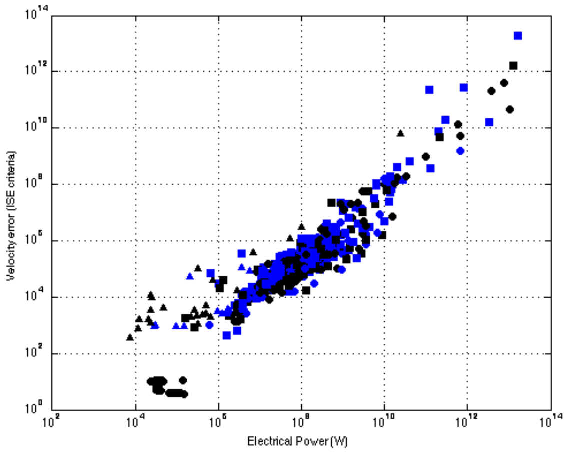

Figure 9. Comparison between velocity control performances and electrical power.

This structure allows us to solve the problem by changing the loading and unloading process of our laser cutter by an automatic loader. Using this solution, we may expect a velocity of ca. 8 m/s and a productivity of 13,000 pieces per hour. But in reality, performances would be lower because of the cutting process which should be synchronized with the motion of the conveyor belt.

4. Conclusions and outlook

This paper presented an approach to integrate optimization in early design process of mechatronic systems. This approach aimed to perform optimization from the preliminary design stage of multidisciplinary devices. To optimize both structure and parameters of a mechatronic device, a strategy based on the evolutionary case-based design approach has been developed. In this approach, we integrated computational and parametric optimization in the embodiment process of multidisciplinary devices. The design approach has then been applied to a practical study-case which shown how it works and how the optimization can be used as a design method. The application to an industrial case to validate the approach and the development of a software platform to realize the topology optimization of the mechatronic system are currently in development and will be the subject of further papers. This software platform totally matches what has been expressed as a key orientation in [27].

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